CEPHEIDS IN THE LMC: RESULTS FROM THE MACHO PROJECT

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Abstract

The approximately 1500 Cepheid variables in 22 LMC fields of the MACHO Project survey have been calibrated and analysed. In this paper, we report improved period ratios for a total of 73 beat Cepheids and provide a first look at the Fourier decomposition parameters for both singly- and doubly-periodic Cepheids. We also note some an unusual amplitude-changing pulsator.

1 Introduction

The MACHO Project has been collecting photometry of stars in LMC fields for over 1400 days at this writing and has already provided a wealth of important new information on variable stars - see [1],[2],[3], [4]. There is, naturally, great interest in the classical Cepheid variables which are used to calibrate the extragalactic distance scale. At present our Cepheid catalogue contains 1466 single-mode (classical) and 73 double-mode (beat) Cepheids. Most of these stars have between 300 and 1100 individual epochs of two-color photometry. We have determined periods for all stars using the full dataset and have generated finder charts, Fourier amplitudes, phases, and ratios and will submit a full analysis of these results in the near future. This paper contains a brief summary of interesting intermediate results, including a list of improved period ratios for LMC beat Cepheids.

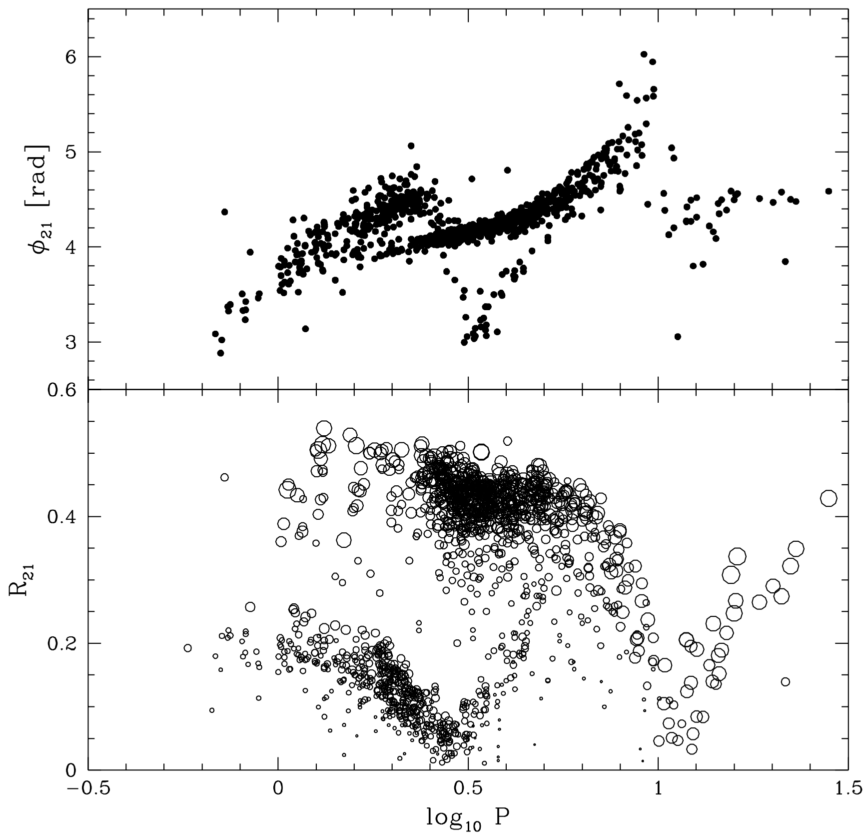

Figure 1: The Fourier amplitude ratios and phase differences for stars with phase difference uncertainty less than 0.1 rad and amplitude ratio uncertainty less than 0.05 in the V bandpass. The size of the amplitude ratio symbol is proportional to the amplitude of the lowest order amplitude.

2 Fourier Decomposition

The properties of lightcurve shapes are observables which are not affected by reddening or distance. Furthermore, both the photometry and period of light variation can usually be determined with high precision. Therefore, it is of considerable interest to investigate whether lightcurve shape is correlated with other physical quantities that are, in practice, more difficult to determine, such as position in the instability strip, pulsation mode, and metallicity.

Fourier coefficients for LMC Cepheids have been most recently discussed by [6]. As a by-product of a search for evidence of microlensing toward the LMC, the EROS collaboration detected 72 Cepheids in their 0.4 square degree field. Approximately 1000 epochs of photometry in the B and R bandpasses were obtained. They discuss the low-order Fourier coefficients so derived.

We have undertaken Fourier decomposition of our lightcurves for order n=12 using the technique described by [7]. The quality of our Fourier fits has been significantly improved by the length of the time series - now three to four times as long as that reported in [8]. The division between overtone and fundamental Cepheids is now even more distinct and there is also an obvious dependance of R_{21} on the amplitude R_1. The so-called long-period s Cepheid sequence is also better defined. Examples of the run of Fourier parameters with photometric period are given in Figure 1. The 2:1 resonance is clearly located by this data at $\log_{10}$ P = 1.05 $\pm$ 0.03.

The run of Fourier parameters with period defined by this sample will ultimately be useful in defining a simple parameterization of lightcurve shape with period, peak-to-peak amplitude and bandpass.

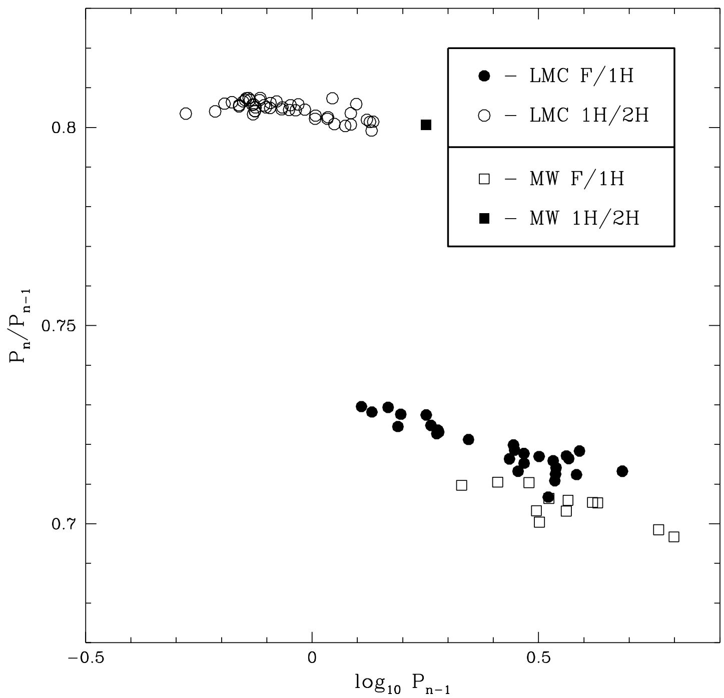

Figure 2: The Petersen diagram for 73 beat Cepheids in the LMC and 14 in the Galaxy.

3 Beat Cepheids

The metallicity sensitivity of the period ratios of beat Cepheids make them especially interesting. The sample of 45 stars reported in [1] has been enlarged and refined by the addition of two more years of observations. The periods and period ratios reported here were obtained by a simultaneous weighted least-squares fit to the principal frequencies and their harmonics, and mixing terms up to order 3. Table 1 contains improved period ratios for beat Cepheids in the LMC. The columns, from left to right, are the designation using equinox J2000.0 coordinates, the internal identifier, the longest principal period in days, the ratio of the two periods present, and the mode identification. Additional data on these stars will be presented in [5]. We note that there are 75 entries in this table but that two of the stars are found in overlap regions of different fields and so the total number of distinct stars is 73. A plot of period ratio versus period for the 75 entries is shown in Figure 2. We also present the R-band P-L relation using the longer of the two principal periods in Figure 3.

The lightcurve geometry of the 2H mode can be extracted from the existing 1H/2H lightcurves. We find that there is no significant power present at any of the harmonics of the 2H period. The Fourier amplitude ratio R_{21} is shown in Figure 4 as a function of period. Note the two distinct sequences. R_{21} seems to approach zero for the 2H mode when P_{2H} is about 1.2 days, which allows us to confine our search for singly-periodic 2H to below this period. The power spectrum for a typical 1H/2H Cepheid is shown in Figure 5.

4 Unusual Cepheids

We have found a number of examples of stars which are apparently changing their amplitudes. The most spectacular of these is `MACHO*05:12:08.3-68:32:11` which has a period of 0.763 days and may be an RR Lyrae star. The R lightcurve for this star is shown in Figure 6.

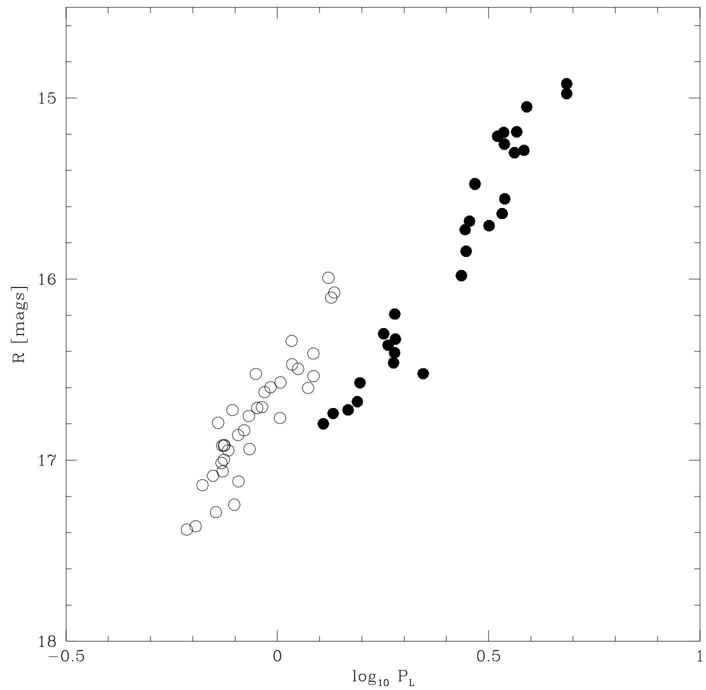

Figure 3: The Period-Luminosity relation for 73 beat Cepheids in the LMC. The symbols have the same meaning as in Figure 2.

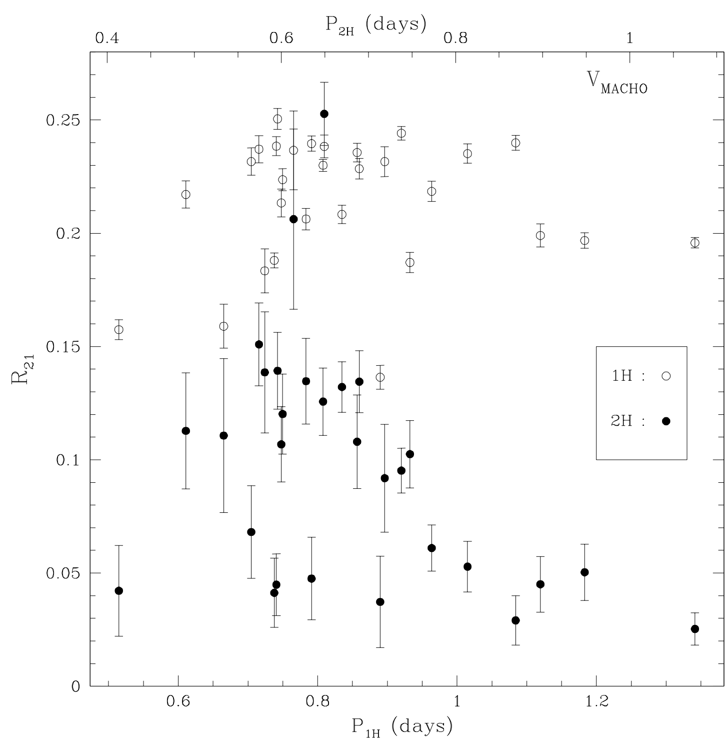

Figure 4: R_{21} for the instrumental MACHO V band. Note the two distinct sequences, as well as the decrease of the 2H mode as the 2H period approaches 1.2 days.

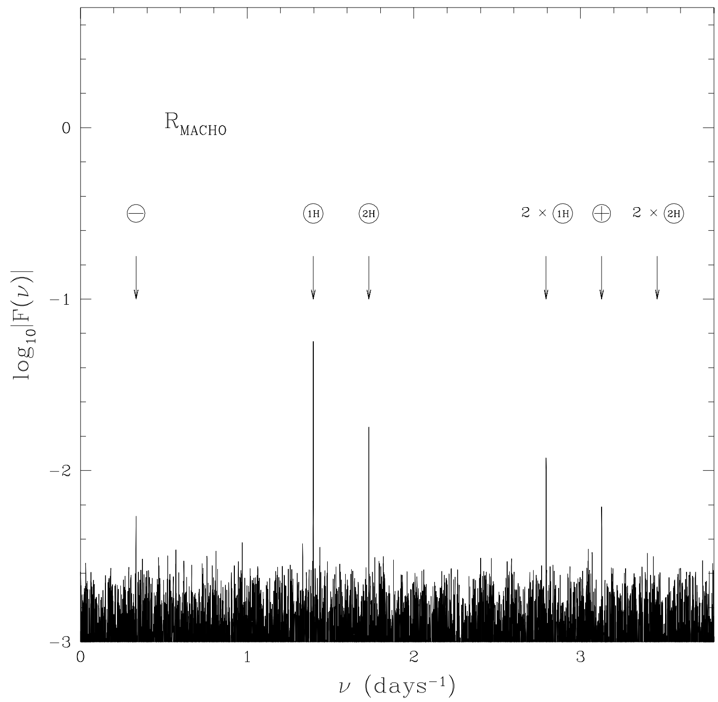

Figure 5: A typical 1H/2H beat Cepheid power spectrum (80.7080.2618) in the instrumental MACHO *R* band. The 1H and 2H frequencies and their harmonics are labelled, as are the sum and difference frequencies. Note the abscence of any 2H harmonics, which is typical for these stars.

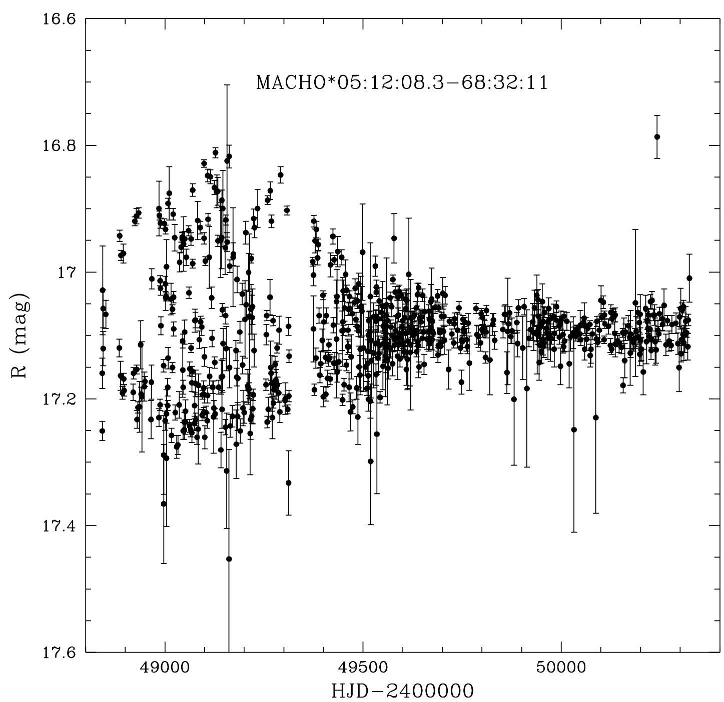

Figure 6: The lightcurve of `MACHO*05:12:08.3-68:32:11` during an interval of 1480 days. This star has a period of 0.763 days and may be related to the RR Lyrae stars.

Table 1. Improved LMC Beat Cepheid Period Ratios

Cepheid	Identifier	P_{n-1} *(days)*	P_n/P_{n-1}	Modes
MACHO*05:11:39.9−68:49:58	79..5022...339	0.526263(000)	0.803491(007)	1H/2H
MACHO*05:38:51.1−69:49:23	81..9485....45	0.610977(003)	0.804052(014)	1H/2H
MACHO*05:48:55.2−70:30:02	12.11168...150	0.640693(004)	0.805979(018)	1H/2H
MACHO*05:15:35.2−68:57:07	79..5747...197	0.665186(002)	0.806371(008)	1H/2H
MACHO*05:15:05.4−69:39:55	5..5615..2564	0.689981(002)	0.805317(012)	1H/2H
MACHO*05:15:06.3−69:39:54	78..5615....82	0.689979(003)	0.805597(013)	1H/2H
MACHO*05:35:11.1−70:17:05	11..8873...189	0.704754(002)	0.806546(007)	1H/2H
MACHO*05:16:28.6−69:36:33	78..5858...301	0.711553(004)	0.806921(014)	1H/2H
MACHO*05:24:13.9−68:49:34	80..7080..2618	0.715870(002)	0.807350(006)	1H/2H
MACHO*05:30:01.9−69:11:39	82..8042...142	0.724083(003)	0.807404(008)	1H/2H
MACHO*05:26:02.1−69:52:09	77..7427...306	0.729244(004)	0.806918(012)	1H/2H
MACHO*05:37:47.1−70:51:43	11..9348....78	0.737786(001)	0.805670(008)	1H/2H
MACHO*05:26:01.5−69:30:42	77..7432...248	0.740810(002)	0.803312(006)	1H/2H
MACHO*04:58:53.0−68:51:07	18..2965...104	0.742535(004)	0.805778(012)	1H/2H
MACHO*05:16:28.5−69:25:35	79..5861..5053	0.747883(002)	0.804089(005)	1H/2H
MACHO*05:16:28.5−69:25:35	78..5861...239	0.747873(004)	0.804132(010)	1H/2H
MACHO*05:34:31.9−69:45:15	81..8760...204	0.749790(004)	0.805021(013)	1H/2H
MACHO*05:15:49.4−68:41:52	2..5750..2010	0.765462(005)	0.806873(011)	1H/2H
MACHO*05:09:29.8−68:21:20	2..4788....82	0.768301(002)	0.807441(011)	1H/2H
MACHO*05:23:13.8−69:36:36	78..6947..2839	0.783376(003)	0.805540(013)	1H/2H
MACHO*05:34:28.5−68:57:01	82..8772....88	0.791229(002)	0.805080(008)	1H/2H
MACHO*05:38:45.4−70:36:11	11..9473...117	0.807845(003)	0.804919(016)	1H/2H
MACHO*05:21:25.4−69:52:52	78..6701...236	0.809516(008)	0.806159(015)	1H/2H
MACHO*05:23:59.1−69:15:30	80..7073...142	0.834857(002)	0.806534(006)	1H/2H
MACHO*05:34:34.6−70:18:20	11..8751...129	0.856631(005)	0.804536(016)	1H/2H
MACHO*05:46:42.8−70:40:50	12.10803...112	0.859789(006)	0.805044(013)	1H/2H
MACHO*05:24:33.2−70:09:30	7..7181..1511	0.889713(007)	0.804411(016)	1H/2H
MACHO*05:21:16.6−69:52:00	78..6580...150	0.896286(006)	0.805608(016)	1H/2H
MACHO*05:23:10.0−70:28:45	6..6934....67	0.920147(002)	0.804300(006)	1H/2H
MACHO*05:30:11.7−69:52:02	77..8032...175	0.932506(003)	0.805776(008)	1H/2H
MACHO*05:49:27.6−71:32:07	15.11153....34	0.963677(004)	0.804477(009)	1H/2H
MACHO*05:47:11.7−70:41:10	12.10803....77	1.015097(010)	0.802180(016)	1H/2H
MACHO*05:07:44.6−68:35:20	19..4421...403	1.017522(012)	0.802970(021)	1H/2H
MACHO*05:21:05.4−68:23:35	3..6602....41	1.081242(006)	0.802169(012)	1H/2H
MACHO*05:10:15.3−68:20:28	2..4909....67	1.084074(006)	0.802568(012)	1H/2H
MACHO*05:25:59.2−69:49:13	77..7428...149	1.108829(035)	0.807335(033)	1H/2H
MACHO*05:45:22.1−70:50:12	12.10558...923	1.119640(007)	0.800828(011)	1H/2H
MACHO*05:43:20.9−71:08:48	15.10191....50	1.183152(010)	0.800353(023)	1H/2H
MACHO*05:09:08.0−68:56:43	1..4658....66	1.217551(006)	0.803593(014)	1H/2H
MACHO*05:07:37.0−69:12:47	1..4412...130	1.217977(005)	0.800710(009)	1H/2H

Cepheid	Identifier	P_{n-1} *(days)*	P_n/P_{n-1}	Modes
MACHO*05:49:28.9−70:22:40	12.11170....25	1.251631(005)	0.805851(020)	1H/2H
MACHO*05:39:29.3−70:38:20	11..9593....90	1.285135(010)	0.729568(007)	F/1H
MACHO*05:02:09.7−68:51:32	1..3570....55	1.321197(010)	0.801925(015)	1H/2H
MACHO*05:20:19.7−70:42:29	13..6446....38	1.341420(008)	0.801375(014)	1H/2H
MACHO*05:37:36.2−69:44:20	81..9244....71	1.352937(012)	0.799210(024)	1H/2H
MACHO*05:16:23.4−68:35:26	2..5873....67	1.355534(011)	0.728205(008)	F/1H
MACHO*04:54:03.4−68:52:02	18..2239....43	1.364201(013)	0.801439(021)	1H/2H
MACHO*05:41:19.1−70:16:35	11..9841....64	1.471403(010)	0.729375(008)	F/1H
MACHO*05:27:59.9−69:37:20	77..7673...103	1.546895(023)	0.724540(012)	F/1H
MACHO*05:15:31.3−68:50:11	79..5748...100	1.569342(023)	0.727638(011)	F/1H
MACHO*05:36:54.7−70:08:10	81..9117...120	1.785987(023)	0.727440(013)	F/1H
MACHO*05:49:14.2−71:09:53	15.11158....33	1.829270(018)	0.724838(010)	F/1H
MACHO*05:33:56.7−68:53:29	82..8652....67	1.884106(038)	0.722736(017)	F/1H
MACHO*04:49:10.1−67:51:53	47..1407....18	1.894536(040)	0.723646(017)	F/1H
MACHO*04:51:31.3−67:48:45	47..1771....30	1.896089(033)	0.723350(014)	F/1H
MACHO*05:00:55.1−69:16:32	18..3322...549	1.904173(019)	0.723137(008)	F/1H
MACHO*04:54:55.0−69:14:12	18..2354....83	2.214457(038)	0.721260(016)	F/1H
MACHO*05:36:31.4−69:28:16	81..9127....78	2.726629(116)	0.716381(036)	F/1H
MACHO*05:06:02.7−68:06:02	19..4186...876	2.782543(027)	0.719885(011)	F/1H
MACHO*05:23:13.8−70:13:46	6..6937....46	2.798537(130)	0.718560(035)	F/1H
MACHO*05:27:06.1−70:19:38	7..7541....17	2.849367(026)	0.713247(010)	F/1H
MACHO*05:26:18.8−70:31:56	7..7417....22	2.935517(022)	0.717742(007)	F/1H
MACHO*05:33:39.4−69:54:55	81..8636....55	2.937037(030)	0.715276(011)	F/1H
MACHO*05:15:31.1−69:18:04	79..5741....67	3.170829(048)	0.716971(011)	F/1H
MACHO*05:21:54.4−69:23:04	78..6708....26	3.321481(020)	0.706737(006)	F/1H
MACHO*05:29:36.0−69:40:28	77..8035....22	3.405098(050)	0.715876(012)	F/1H
MACHO*05:27:15.8−69:43:43	77..7550....42	3.433695(026)	0.710865(008)	F/1H
MACHO*05:31:09.0−70:05:11	77..8271....26	3.446769(025)	0.712526(007)	F/1H
MACHO*05:35:56.8−70:04:51	81..8997....28	3.455026(042)	0.714131(011)	F/1H
MACHO*05:34:59.5−71:12:35	14..8859....14	3.641905(038)	0.717143(010)	F/1H
MACHO*05:30:59.9−69:49:17	77..8154....22	3.685674(030)	0.716438(007)	F/1H
MACHO*05:06:29.3−68:54:20	1..4174....23	3.834480(042)	0.712401(010)	F/1H
MACHO*05:03:58.5−69:25:38	1..3804....26	3.892839(043)	0.718364(010)	F/1H
MACHO*05:20:07.3−70:04:09	78..6456....11	4.840916(055)	0.713243(012)	F/1H
MACHO*05:20:07.1−70:04:08	6..6456..4343	4.840942(169)	0.713247(034)	F/1H

5 Work in Progress

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